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13. ABSTRACT (Maximum 200 words)

The research was aimed at producing quantum wire superlattices with dimensions below 10nm by directly using molecular beam epitaxy. Two (2D) and three dimensional (3D) carrier confinement is achievable relatively easily when the confinement length scale is larger than 100 nm. This is the dimensional range of the so called mesossopic devices. All the technologies which permit this mesoscopic regime are based on lithography (electrons or ions) processing which will be used for producing a depletion layer or a lateral band gap modulation wiht a strain field. Unfortunately the interesting effects associated with the presence of a superlattice and quantization are not found until the structure dimensions are well below the 50nm range. There are presently few processing techniques which will permit reaching these dimensions.

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AFOSR FINAL RESEARCH REPORT FOR THE PERIOD 1988-1991.
CONTRACT #88-0334

Principal investigator P.M.Petroff
University of California. Santa Barbara.

Students paid on contract: Yuan Jing Li, Mark Miller, S.Chalmers.

Post doctoral researcher paid on contract: Dr. Klaus Ensslin and W.Beinstingl.

Research Report:

1) Growth of quantum wire superlattices on vicinal surfaces:

The research was aimed at producing quantum wire superlattices with dimensions below 10nm by directly using molecular beam epitaxy. Two(2D) and three dimensional (3D) carrier confinement is achievable relatively easily when the confinement length scale is larger than 100nm. This is the dimensional range of the so called mesoscopic devices. All the technologies which permit this mesoscopic regime are based on lithography (electrons or ions) processing which will be used for producing a depletion layer or a lateral band gap modulation with a strain field. Unfortunately the interesting effects associated with the presence of a superlattice and quantization are not found until the structure dimensions are well below the 50nm range. There are presently few processing techniques which will permit reaching these dimensions.

The direct crystal growth of quantum wire superlattices is made possible through the growth of the so called "Tilted superlattices" (TSL). These superlattices are similar to the usual quantum well superlattices, however, the orientation of the quantum well with respect to the substrate surface as well as their thickness can be continuously changed during growth. The basic principle for this epitaxial growth method was developed and demonstrated 3 years ago during the course of this contract. It involves the alternate deposition of fractional submonolayers m and n (m,n <1) of two semiconductors (A)m-(B)n with different band gaps on a substrate comprising a well ordered array of steps. The ordered vicinal surface is made of monoatomic atomic steps with a periodic spacing L. L may be adjusted by choosing the substrate vicinal angle and the ordering of the steps by growth of a buffer layer in the step flow growth regime. The techniques developed for producing vicinal surfaces with ordered step arrays were part of this research contract and were based on the extensive analysis of RHEED patterns (see attached reprints).

The TSL growth method has been successfully demonstrated both by molecular beam epitaxy (MBE) for the GaAs-AlGaAs system. It has also been applied successfully to the GaSb-AlSb system and with the appropriate growth conditions should be applicable to a wide variety of semiconductors or even metal or insulators systems (see attached papers).

In this contract, the growth method has successfully been used to demonstrate 2D quantum confinement by optical methods.

Control of the quantum wire dimensions and uniformity are prerequisites to achieving the most desirable properties of the 2D quantum confinement. The TSL growth requires an extremely fine control over the $(A)_m$-$(B)_n$ fractional monolayers coverage. Indeed the vertical interface superlattice is only achieved for a coverage, p=m+n=1 per deposition cycle. A 1% deviation in the flux deposition will produce a 30° change in the TSL orientation for a GaAs (100) vicinal surface with a 1° misorientation. This required accuracy (better than 1%) in the flux control is presently impossible to achieve in MBE as well as MOCVD over large substrate areas.

To relax these stringent growth requirements, we have introduced a novel superlattice, namely the Serpentine superlattice(SSL). In the SSL, a "build in" 2D quantum wire confinement is present. As shown in the schematic in Figure 1, the meandering interfaces of the quantum well as well as their thickness is varying along the substrate normal direction.

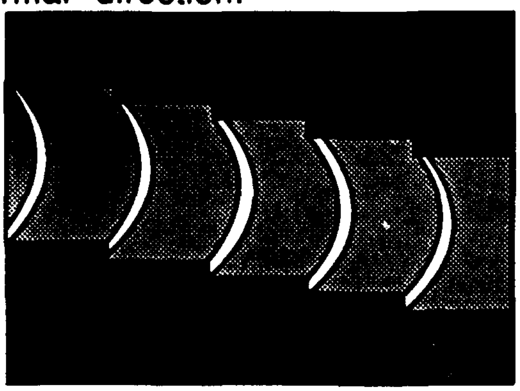

Figure 1: Schematic of a single crescent serpentine superlattice (SSL). The quantum well have parabolic interfaces. The 2D confinement ant quantum wire effects are achieved at the apex of each parabola.

This meandering of the quantum wells in the SSL is achieved by varying the per cycle coverage during deposition. One coverage cycle corresponds to the deposition of m monolayer of $(AlAs)_m$ or $(AlGaAs)_m$ followed by n monolayer of $(GaAs)_n$ with m and n<1. If the cycle coverage is repeated and kept constant during the growth, a TSL is obtained. However a linear variation in the per cycle coverage between two values p_A and p_B such that $p_A<1<p_B$ as a function of distance along the growth direction, yields a superlattice of GaAs quantum wells with interfaces in the shape of parabola.

The parabola equation is given by:

$$x= Ky^2/2 \qquad (1)$$

Where the axis x and y ar along the [110] and [001] directions respectively and K is the curvature.

We note that the apex of the parabola correspond to the coverage $p=m+n=1$ value and also corresponds to the point of maximum quantum well width W:

$$W= nd/tg\alpha \qquad (2)$$

with the spacing between steps along the [001] direction=2.68Å for GaAs and a substrate vicinal angle α.

The curvature K of the parabola is directly related to the quantum confinement along the growth direction while the lateral confinement is determined by W. This curvature may be chosen at will since it is determined by the linear ramping rate of the per cycle coverage with

$$K=2[p_B-1]\ /tg\alpha \qquad (3)$$

With this approach, one can afford to start ramping the per cycle coverage from $p_A=0.9$ to a value $p_B=1.1$ and thus make certain that variations in the deposition flux (2-3%) over the wafer will still insure the presence of regions in the film which contain identical quantum wires.

One of the main characteristics of the quantum wire confinement is the photoluminescence (PL) linear polarization for the electric vector parallel or perpendicular to the wire axis. As a proof of the quantum wire superlattice existence over large wafer areas, we show in Figure 2 a plot of the polarization as a function of position for a quantum wire superlattice imbedded in the SSL structure shown in Figure3. The small variation in this ratio (2-3%) for this wafer is similar to that observed in the ground state energy measured by PL for a quantum well included in the same wafer as the SSL. These variations can be traced to perhaps temperature variations across the wafer or to the Al content in the barrier material. The important point is that this type of uniformity could not be achieved for quantum wires made using the TSL method which will show variations of 50% or more over the same distance.

The cross section transmission electron micrograph shown in Figure 3 for a double crescent serpentine superlattice shows the parabolic shaped quantum wells and barriers. The chemical contrast imaging mode used in this micrograph indicates that the programmed compositional variations between the $Ga_{.5}Al_{.5}As$ barriers and the GaAs quantum well regions are not present in the structure. In fact, this micrograph indicates that some of the Al that was supposed to be present in the barrier region has been trapped during growth in the quantum well and quantum wire regions of the structure.

The photoluminescence studies of SSL quantum wire array for light with the electric vector component parallel and perpendicular to the wire axis are shown in Figure 4. The observed optical anisotropy observed both in PL and in resonant excitation PL experiments is well understood theoretically as originating from the 2D confinement associated with the quantum wire superlattice. A careful comparison between theory and experiments further indicates that a sizable portion of the Al stays trapped in the GaAs wire regions of the structure. This poor segregation of the Al has been tentatively attributed to kinetics of growth for step flow mode which are different for the GaAs and the AlAs. A two temperatures deposition approach is being implemented to alleviate this problem.

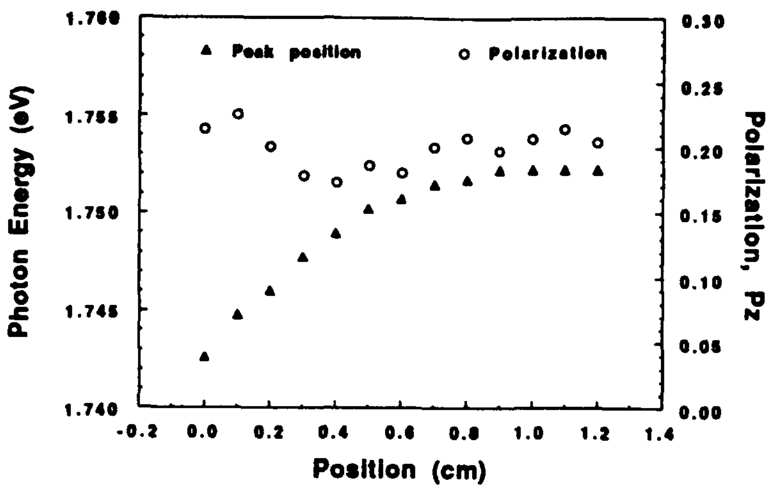

Figure 2: Photoluminescence and polarization anisotropy of a GaAs-AlGaAs SSL as a function of position on the wafer.

Figure 3: Cross section transmission electron micrograph of a Serpentine superlattice.

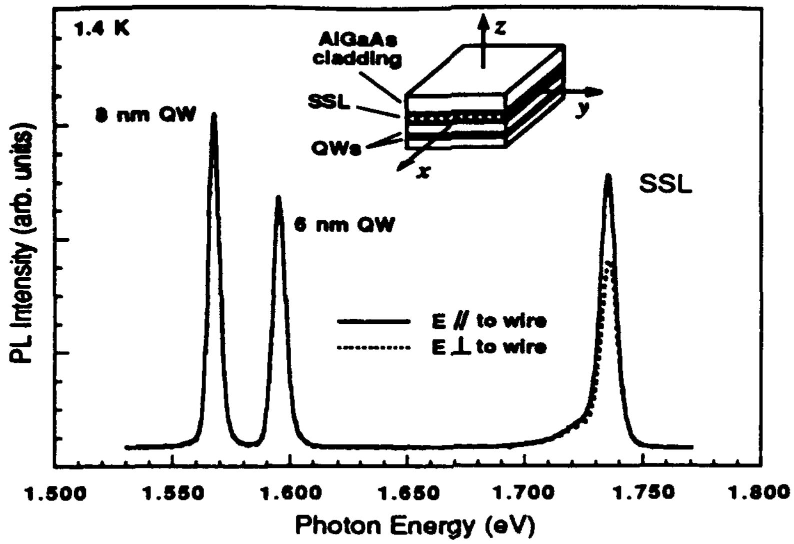

Figure 4: Polarized photoluminescence as a function of photon energy for a GaAs-AlGaAs SSL. The inset shows the geometry of the polarization experiment. Two test quantum wells also were included in the same sample. These show no polarization effects.

2)Focused ion beam applications of the processing of mesoscopic structures.

We have continued our studies of the enhanced interdiffusion between Ga and Al in quantum well structures. Ga^+ ions produced by a focused ion beam(FIB) have been used. We have shown that the unexpectedly deep interdiffusion we have observed in QW structures is related to ion channeling. This phenomenon allows to produce a complete annealing of the ion induced damage, maximize the interdiffusion (80-100meV band gap changes are produced on a nanometer scale) and optimize the electronic properties of the material .

We have demonstrated that the FIB probe size(600Å) is also preserved deep below the surface (2000Å). This absence of ion straggling when channeling effects are used is very advantageous for producing quantum wires and boxes.

We have made use of this effect for studying the magnetotransport through an antidot lattice in GaAs-AlGaAs heterostructures. A regular array of antidots with periodicities ranging from 200 to 500nm have been produced by FIB implantation of a 2 DEG located at the GaAs/AlGaAs interface. The low temperature magnetotransport measurement reveal a large negative magnetoresistance which we attribute to electron localization. Under illumination we observe mobility changes larger than 20 in the antidot lattice. We also observe implantation conditions which yield a zero depletion layer antidot structure.

Finally, we have implemented an all **in situ** processing procedure that allows the connection of the UHV FIB system with the MBE deposition systems and reactive ion etching chamber. We have started using the facility for processing several novel devices. We have fabricated the first reversed HEMT using focused ion beam.

We have also demonstrated the first resonant tunneling devices with room temperature negative differential resistance equal to those of devices produced by direct MBE growth. We have also demonstrated the concept of buried stressors for the lateral band gap modulation on a mesoscopic scale. This work will be pursued under the sponsorship of NSF for the next 5 years. It is becoming clear that the FIB in situ approach offers the possibility of producing discrete devices on wafers and will permit the integration of widely different types of devices on the same wafer.

3) Students working towards a Ph.D or having completed a degree.

Scott Chalmers (MS, U Texas).Shared with H.Kroemer and A.C.Gossard.(PH.D. completed September 1991)

M. Miller (MS, U Colorado). Scheduled PH.D. completion January 1991.

Y.J.Li (M.S. UCSB). Scheduled Ph.D completion for October 1992.

LIST OF PUBLICATIONS (published, under press or submitted January 1989- October 1991)

1) " BAND GAP MODULATION IN TWO DIMENSIONS BY MBE GROWTH OF TILTED SUPERLATTICES AND APPLICATIONS TO QUANTUM CONFINEMENT STRUCTURES." P.M.Petroff, J.M.Gaines, M.Tsuchiya, R.Simes, L.Coldren, H.Kroemer, J.English, and A.C.Gossard. J.Crystal Growth.95,260,(1989).

2) " OPTICAL ANISOTROPY IN A QUANTUM WELL WIRE ARRAY WITH TWO DIMENSIONAL QUANTUM CONFINEMENT " M.Tsuchiya, J.M.Gaines, R.H.Yan, R.J.Simes, P.O.Holtz, L.A.Coldren, and P.M.Petroff. Phys Rev. Lett. 6,466 (1989).

3) " ADVANCES IN EPITAXIAL GROWTH OF SEMICONDUCTORS: NEW ARCHITECTURES AND TILTED SUPERLATTICES. Physics Today, S.64, (1989).

4) " SPONTANEOUS GROWTH OF COHERENT TILTED SUPERLATTICES ON VICINAL (100) GaAs SUBSTRATES" M.Tsuchiya, P.M.Petroff and L.A.Coldren. Appl. Phys Lett. 54, 1690, (1989).

5) " NOVEL CRYSTAL ARCHITECTURES IN EPITAXIAL GROWTH " P.M.Petroff.et al. "Fundamental issues in heteroepitaxy_ A DOE Council on Materials Science panel report" J.Mater. Res. Vol.5,4 852 (1990).

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7) " OPTICAL PROPERTIES OF GaAs/GaAlAs QUANTUM WIRES AND BOXES PROCESSED BY FOCUSED ION BEAM IMPLANTATION OF QUANTUM WELL STRUCTURES" F.Laruelle, P.Hu, X. Qian, R.Simes, R.Kubena, W.Robinson, J.Merz and P.M.Petroff. J.Vac.Sci.Tech. B , 7, 6, 2034 (1989).

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9) " A REFLECTION HIGH ENERGY ELECTON DIFFRACTION STUDY OF (100) GaAs VICINAL SURFACES" S.A.Chalmers, A.C.Gossard, P.M.Petroff, J.M.Gaines, and H.Kroemer J Vac. Sci. Technol. B 7, 6, 1357 (1989).

10) " AlGaAs-GaAs LASERS WITH QUANTUM WIRE ACTIVE REGIONS" M.Tsuchiya, L.Coldren and P.M.Petroff. Proceedings of the IOOC-89 meeting p 19C1 Kobe Japan 1989.

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22) " NOVEL APPROACHES IN 2 AND 3 DIMENSIONAL CONFINEMENT STRUCTURES: PROCESSING AND PROPERTIES. P.M.Petroff, K.Ensslin, M.Miller, S.Chalmers, H.Weman, J.Merz, H.Kroemer, and A.C.Gossard. Proceedings of ICPEOM Heraklion. J.Superlatt. and Microstructures 8, 35, (1990).

23) " MBE GROWTH OF TILTED SUPERLATTICES: ADVANCES AND NOVEL STRUCTURES." P.M.Petroff, M.Miller, Y.T.Lu, S.Chalmers, H.Metiu, H.Kroemer, and A.C.Gossard. J.Crystal Growth 111, 360 (1991).

24) " A REFLECTION HIGH ENERGY ELECTRON DIFFRACTION STUDY OF AlAs/GaAs TILTED SUPERLATTICE GROWTH BY MIGRATION ENHANCED EPITAXY" S.A.Chalmers, A.C.Gossard, P.M.Petroff and H.Kroemer. J.Vac. Sci. Technol. B8,431 (1990).

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26) " OPTICAL STUDIES OF DIRECT MODULATION DOPING AND QUANTUM WIRE FORMATION BY FOCUSED Si ION BEAM IMPLANTATION" Y.J.Li, S.Sasa, W.Beinstingl, M.S.Miller, Z.Xu, G.Snider and P.M.Petroff J.Vac Sci. Technol. B (to be published Nov. Dec. 1991).

27) " OPTICAL PROPERTIES OF QUANTUM STRUCTURES FABRICATED BY Ga FOCUSED ION BEAM IMPLANTATION" W.Beinstingl, Y.J.Li, H.Weman, J.Merz, and P.M.Petroff. J.Vac Sci. Technol. B (to be published Nov. Dec. 1991).

28) " ANISOTROPIC ELECTRON TRANSPORT THROUGH A RECTANGULAR ANTIDOT LATTICE" K.Ensslin, S.Sasa, T.Deruelle, and P.M.Petroff. J.Superlatt. and microstructures (to be published 1991).

29) " NANOSTRUCTURES PROCESSING BY FOCUSED ION BEAM IMPLANTATION" P.M.Petroff, Y.J.Li, Z.Xu, W.Beinstingl, S.Sasa, and K.Ensslin. J.Vac Sci. Technol. B (Nov. Dec. 1991).

30) " SELECTIVE FORMATION OF GaAs/AlGaAs MODULATION DOPED STRUCTURES AND WIRE STRUCTURES BY USING Si FOCUSED ION BEAM IMPLANTATION." S.Sasa, Y.J.Li, M.Miller, Z.Xu, K.Ensslin and P.M.Petroff. J.Vac Sci. Technol. B (to be published Nov. Dec. 1991).

31) " SERPENTINE SUPERLATTICE: CONCEPT AND FIRST RESULTS. M.S.Miller, C.E.Pryor, H.Wehman, L.A.Samoska, H.Kroemer, and P.M.Petroff. J.Cryst growth 111, 323(1991).

32) " HOW BIG IS AN ANTIDOT" T.Deruelle, K.Ensslin, P.M.Petroff, A.Efros and F.Picus. Phys Rev. B (submitted 1991).

33) " SERPENTINE SUPERLATTICES OF AlGaAs GROWN ON GaAs VICINAL SURFACES" M.S.Miller, H.Weman, C.E.Pryor, M.Krishnamurty, P.M.Petroff, H.Kroemer, and J.L.Merz. Phys. Rev Lett. (submitted 1991).

34) " OPTICAL PROPERTIES OF (AlGa)As SERPENTINE SUPERLATTICE QUANTUM WIRE ARRAYS" H.Weman, M.S.Miller, C.E.Pryor, M.Krishnamurty, P.M.Petroff, H.Kroemer, and J.L.Merz. Phys Rev B (to be published 1991).

35) " LUMINESCENCE PROPERTIES OF (Al,Ga)As TILTED SUPERLATTICES COUPLED QUANTUM WIRE ARRAYS." H.Weman, M.S.Miller, C.E.Pryor, P.M.Petroff, H.Kroemer, and J.L.Merz. Phys. Rev. B. (submitted 1991).

36) " MEASURING LINEAR POLARIZATION OF PHOTOLUMINESCENCE AND PHOTOLUMINESCENCE EXCITATION USING A PHOTOELEASTIC MODULATION TECHNIQUE" M.Wassermeier, H.Weman, M.S.Miller, P.M.Petroff, J.L. Merz. J.Appl. Phys. (submitted 1991).

37) " SRUCTURE AND PERFECTION OF GaAs-AlAs SERPENTINE SUPERLATTICES GROWN BY MOLECULAR BEAM EPITAXY" M.Krishnamurty, M.Miller, H.Kroemer and P.M.Petroff. Appl. Phys. Lett. (submitted 1991)

LIST OF ORAL PRESENTATIONS (1989-1991):

1) "Ultrastructures for 1 and 2 dimensional confinement in compound semiconductors" **Invited talk.** Workshop on surfaces and surface reactions. Wickenburg. (january 1989).

2) " Two dimensional band gap engineering in III-V compounds semiconductors: Applications to quantum wire structures and devices". **Invited talk**. Optical society of America, Salt Lake city. (march 1989).

3) " Epitaxial growth and self organization on vicinal surface" **Invited talk**. IBM(Almaden March 1989.)

4) " DARPA Workshop on integrated optoelectronics"_ presentation on quantum wire superlattices and applications. (Hilton Head. March 1989)

5) " Novel crystal architectures for 2 and 3D confinement" **Invited talk**. IBM seminar on semiconductor physics. (Yorktown Heights June 1990)

6) " MBE growth of Tilted Superlattices and Quantum wires" **Invited talk**. First advanced meeting on advanced processing and characterization. (Tokyo Japan Oct. 1989)

7) " MBE growth of tilted superlattices on vicinal surfaces" **Invited talk** .7th International workshop on future electron devices (Toba Japan October 1989)

8) " Novel crystal growth for nanostructure superlattices" **Invited talk** American Vacuum Society meeting (Boston October 1989)

9) " Direct epitaxial growth of quantum, structures with 2 and 3 D carrier confinement" **Invited talk.** NATO workshop on kinetics of ordering and growth at surfaces. (Italy-September 1989)

10) " Novel Crystal growth for carrier confinements in 2 and 3 D" **Invited talk** DUPONT (Maryland October 1989).

11) " Crystal growth and nanostructures processing" **Invited talk** NRC (Ottawa February 1990)

12) " Optical Properties of MBE grown quantum wire superlattices " **Invited talk**, American Physical Society ,(Annaheim March 1990).

13) "Focused Ion Beam Processing of GaAs Nanostructures" **Invited Talk** UCSD (La Jolla, February 1990)

14) " Direct growth of nanostructures" **Invited Talk**. Gordon Conference on Chemistry of electronic Materials. (Ventura February 1990)

15) " Tilted superlattices quantum wires and boxes" **Invited talk** . Gordon Conference on structures. (New Hampshire. July 1990).

16) " MBE growth of Tilted superlattices: Advances and novel structures." P.M.Petroff, M.Miller, Y.T.Lu, S.Chalmers, H.Metiu, H.Kroemer, and A.C.Gossard. **Invited talk**. MBE VI International conference. LaJolla (September 1990).

17) " Novel approaches in 2D and 3 D carrier confinement structures: Processing and properties" **Invited talk**. P.M.Petroff, K.Ensslin, M.Miller, S.Chalmers, H.Weman, J.Merz, H.Kroemer, and A.C.Gossard. ICPEOM Heraklion. Crete. (July 1990).

18) " Serpentine superlattice in GaAs: concept and results." M.S.Miller, C.E.Pryor, L.A.Somoska, H.Weman, H.Kroemer, and P.M.Petroff. International conference on the Physics of semiconductors. , Thessaloniki, Greece. (August 1990).

19) " Serpentine Superlattice: Concept and first results. M.S.Miller, C.E.Pryor, H. Weman, L.A.Samoska, H.Kroemer and P.M.Petroff. VIth International Conference on Molecular Beam Epitaxy. SanDiego(Aug. 1990).

20) "Photoluminescence Study of Quantum Wire Arrays in GaAs/AlGaAs Tilted Superlattice Structures" H.Weman, M.S.Miller, P.M.Petroff, H.Kroemer and J.Merz. American Physical Society Meeting Cincinnati(March 1991).

21) " Structure and Luminescence of AlGaAs Serpentine superlattices" M.S.Miller, C.E.Pryor, H.Kroemer, P.M.Petroff and J.Merz". American Physical Society Meeting Cincinnati(March 1991).

22) " In situ reflectance difference spectroscopy of (100) vicinal GaAs and AlAs surfaces." M.Wassermeier, I.Kamiya, D.E.Aspnes, L.T.Florez, and J.P.Harbison. American Physical Society Meeting Cincinnati(March 1991).

23) " Magnetotransport properties of GaAs-AlGaAs antidot lattices" K.Ensslin, T.Deruelle, A.Efros, and P.M.Petroff. American Physical Society Meeting Cincinnati(March 1991).

24) "Atom positioning for band gap engineering of III-V compounds semiconductors on a nanoscale" **Invited talk**. P.M.Petroff. Spring MRS meeting Anaheim. (March 1991).

25) " Growth Processing and properties of quantum wire structures in III-V compounds semiconductors".P.M.Petroff.**Invited talk**. Physics department. University of California., Davis. (Feb. 1991).

26) "Characterization of in-situ MBE grown GaAs quantum well on focused ion beam Si implanted substrates." Z.Xu, M.Miller, W.Beinstingl, Y.J.Li, S.Sasa, and P.M.Petroff. Electronic Materials Conference. Boulder (June 1991).

27) " Anisotropic transport through a rectangular Antidot lattice" K.Ensslin, S.Sasa, T.Deruelle, and P.M.Petroff. EP2DS conference. Nara, Japan (July 1991).

28) "Electronic structure and optical properties of AlGaAs quantum wire arrays formed by serpentine superlattices". P.M.Petroff. **Invited talk**. Workshop on optical properties of mesoscopic semiconductor structures. Snowbird (April 1991).

29) "Nanoscale band gap engineering in GaAs-AlGaAs quantum well structures by focused ion beam." P.M.Petroff, Y.J.Li, S.Sasa, W.Beinstingl, M.Miller. **Invited talk.** Three beam conference. Seattle (May 1991).

30) " Atomic control of crystal growth for band gap engineering on a nanoscale" P.M.Petroff. **Invited talk.** Lund University. Sweden.(June 1991).

31) "Making quantum wire and quantum boxes for optoelectronic devices." **Invited talk**. J.Merz, and P.M.Petroff. European MRS. Strasbourg, France (April 1991).

32) "Crystal growth of tilted superlattices and serpentine superlattices by molecular beam epitaxy and organometallic epitaxy." **Invited talk**. P.M.Petroff. AVS Symposium on Properties of semiconductors with atomic level control. ATT. Bell .Labs. Murray Hill. (March 1991).

33) " Nanoscale band gap engineering and modulation doping in GaAs-AlGaAs quantum well structures by focused ion beam". **Invited talk**. P.M.Petroff, Y.J.Li, Z.Xu, S.Sasa, W.Beinstingl, M.Miller. LEOS symposium on microfabrication for photonic and optoelectronic. Newport Beach. (Aug. 1991).

34) " Optical properties of (Ga,Al)As serpentine quantum wire arrays grown on GaAs vicinal substrates. Conference on Electronic Properties of 2 Dimensional electronic systems. EP2DS-9. Nara Japan. (July 1991).

35) " Structural and optical properties of AlGaAs-GaAs Serpentine superlattices and quantum wires grown by molecular beam epitaxy" P.M.Petroff **invited talk** International confeerence on the Science and Technology of mesoscopic structures. Nara Japan (Nov. 1991).

36) " Mesoscopic band gap engineering using a focused ion beam" P.M.Petroff **invited talk.** Texas Instrument Central Research Laboratory.(Sept. 1991)